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Matrix structures for high volumes and flexibility in production systems

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Abstract

Flexible production systems addressing the requirements from customized products are currently in focus. Especially for the automotive industry flexible and scalable manufacturing systems are of specific relevance, due to the increasing variety and complexity of products and components over the last decades. Flexible and scalable manufacturing systems must not be designed at the expense of the ability to achieve cost effective large scale production. In the following paper a method is outlined that enables assembly line production to achieve high flexibility combined with high profitability. The key feature of this new approach is the elimination of equal cycle times while sustaining a fluently running process. This is achieved by a specific allocation of several operation steps onto specifically arranged work stations and a control system that regulates the appropriate distribution, ensuring the dynamic configurability of the system. As a result, significant higher efficiency of each station will be achieved, without establishing a special sequence for every product or product variant. Hence the discrepancies between flexibility and efficiency is not only resolved but the demand for maximum capacity can necessitate the application of more flexible systems.

Keywords: Flexible manufacturing system; Mass customization; Large scale production

1. Introduction into Automotive Market Conditions

In the automotive industry market conditions have been changing significantly over the last decades. New customer demands, shifts in the global market, new technologies, shorter product life cycles, and political regulations like CO2 edicts lead to new challenges for original equipment manufacturers (OEM) [1,2].

1.1. Effects to portfolios in automotive industry

To utilize the full potential of the global automotive market it is necessary to take into account all potential customers with respect to their individual needs and preferences [3,4]. Invariant uniform products are failing these individualized customers' demands. OEMs are forced to provide a wide diversity of specialized vehicle concepts. This includes different variations of the main car concept up to extensive modifications like using alternative drive trains. Electric vehicles are an example in this field of innovation [5].

Market cycles are shortening, superseded by new developments. The diversity is growing while the product volume per model is decreasing [6]. Considering all the above mentioned changes, it is remarkable that the main principle of an assembly line – established by Henry Ford over a hundred years ago – is still in use today.

As a result of the aforementioned diversifications, an innovative and scalable production system is required that can deal with altering demands and uncertainties. High flexibility connected to high output volumes and scalability is absolute necessary in future automotive production systems [7]. This target can be achieved not only in the automotive industry but in other mass-production-sectors as well by applying the outlined matrix-structures.

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1.2. Relevancy in production systems

As the product results from evoked demands, the way of production responds to the product. So eventually the production system is linked with the demand. This accounts for a process choice that considers the market situation on the whole [8]. Due to expensive investments in automobile production a flexible mixed-model production is required which can deal with all the main issues:

- Product diversity
- Keeping a high output level simultaneously
- Uncertainties in respect to future demands
- Long term design and development
- Increasing electric driven vehicle concepts

1.3. Necessary flexibility for production systems

Hence, future production systems should provide a high ability for flexibility. In this context flexibility can be classified as follows [9]:

- Market flexibility (The ability to adapt to changing market demands)
- Production flexibility (The range of diverse products a system currently can produce)
- Volume flexibility (scalability)
- Product flexibility (The ability to implement new products or change the current set of products)
- Process flexibility (The ability to reconfigure the production system)

As described in section 1.1, market flexibility will be the main objective in automotive industry. Considering the main issues as above identified it means a progression of product flexibility that simultaneously renders mass customization. If time variable trends and connected fluctuations in consumer demands are additionally considered the product system also has to be flexible in volumes. This means the ability to scale the output in short terms for economic reasons. In long term the system must be able to adapt to market conditions by increasing product flexibility. This is of utmost significance in the above commented accelerating market cycles. Production flexibility, volume flexibility as well as product flexibility are all based on the ability to readjust or reconfigure existing processes. Vital demand on any innovative production system for the future will be process flexibility combined with keeping a high output level as well as a high line utilization rate at the same time.

2. Background

In vehicle productions solitary assembly lines for just one product version or specification are uneconomical in respect to demands of customization. To use an assembly line to full capacity an appropriate amount of vehicles must be ordered. To ensure this and considering the necessary market flexibility mixed model assembly lines are preferred [10].

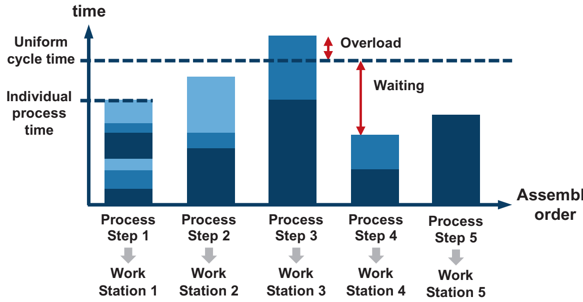

Fig. 1. Allocation of individual assembly steps.

The assembly process of a vehicle is split into several steps, see Fig.1. The given order of sequential arrangement is mainly driven by the physical accessibility of the components of the car. A couple of assembly steps are arranged to a process step. The resulting process steps are allocated to several work stations. At a standard automotive assembly line these stations are mainly manual assembly stations with operating workmen. During the manufacturing process the products have to pass all of the work stations, following the order of installation, thus describing a clearly lineal movement of an assembly line. The distribution of products within the system as well as the pace of production stays constant to enable a stable production control. This constancy also causes a uniform cycle time at every single work cell. This constant time is the maximum available timespan to fulfill required work contents within the separate process steps. In conclusion the process time per process step is restricted by the cycle time which means that the process time of a process step should never overrun the cycle time otherwise overload occurs. Unused time differences between process time and cycle time imply a waste of work capacity by interrupting the process. To match the system wide cycle time to the process times of all work stations the contents of all process steps have to be balanced [11]. In practice, however, even for the assembly of only one product variation it is difficult to synchronize all process times to the cycle time. Gaps arise between the cycle time and the needed process times which cannot be closed, because a following assembly step is too long for the remaining cycle time and cannot be split. See Fig. 1 as an example. In fact the workload and the resulting process time of several work stations are different. This especially applies to the complexity of vehicle manufacturing [12].
Several conditions prevent or disturb the balance between cycle time and process time:

- Unsynchronized process times of several process steps (Mainly technically caused or by the workload of different components and their assembly order)
- Different process times of the same process step (Caused by several variants)
- Temporary additional or omitted process steps (Driven by different workload mainly caused by altering vehicle models and derivations on the same production line)
- Aberration of the optimized sequence of variants (Due to the dynamics of market demands)

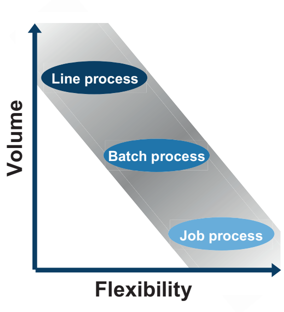

Fig. 2. Relation between flexibility and volume as process choice [13].

This leads to the assumption that flexibility in general and utilization as process choice are excluding. Referring to Krajewaski et al. [13] traditional assembly line concepts struggle to maintain high utilization when producing components with high variances in processing times at the same line, see Fig. 2. Hence a traditional single line alignment is not suitable to deal with future production requirements, see section 1.2. Thus new manufacturing system configurations are required.

3. Matrix structures for production systems

The basic task of assembly planning is to assign the required work scope for an intended product to the available number of workstations and manpower. The cycle time would be the determining factor and identifies the output per fixed time period. The required tasks can be split into assembly steps which can be merged to process steps. Every process step has its own workload and process time witch can vary depending on product variants. Assuming only one product variant for simplifying theoretical conditions, the sum of all process times forms the total production time, proportional corresponding to the total required work.

On the other hand the system provides a certain workmanship. In vehicle assembling the provided output is proportional to the number of employees. For simplification it is assumed that all employees perform at the same level and are evenly allocated to all work stations. Thus all stations will provide equal outputs.

Within an assembling line that operates at 100 % capacity the cycle time multiplied with the sum of work cells is equal to the sum of process times.

$$\text{cycle time} \times \sum \text{work stations} = \sum \text{process time} \quad (1)$$

Because all stations within a classic assembly line are arranged in an alignment it results the necessity for all stations to run equal cycle times. To operate at maximum capacity the given cycle time must be used at 100 % by the process step. Hence the process times of all stations are uniform and equal to the uniform cycle time in a classic assembly line:

$$\text{cycle time} = \text{process time} \quad (2)$$

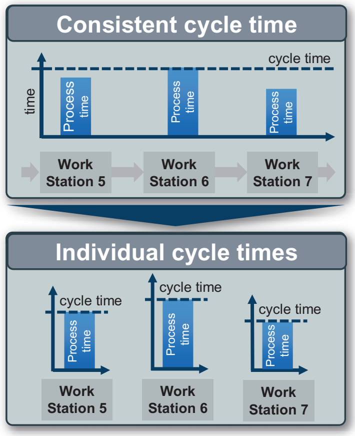

Fig. 3. Individual and uniform cycle times

As shown above, this is practically not possible even in a solitary line. Taking into consideration the increasing diversity of products, the utilization aim of 100 % is even less possible. This leads to the necessity to configure cycle times longer than needed. From this fact waiting times arise. The sum of cycle times is bigger than the sum of process times, see Fig. 1.

If the assembly system is divided into smaller systems thus forming individual sub systems, it appears that under these circumstances the special cycle times of each sub system do not necessarily have to correspond to the (average) cycle time of the complete system. Instead it has to be ensured that the average cycle time resulting from all sub systems corresponds to the average process time resulting from all executed processes.

$$\text{average cycle time} = \text{average process time} \quad (3)$$

First of all this shows that in theory an equal cycle time is not compellent because the single work stations (as sub systems) are partly autonomic systems and can be allowed to vary in their cycle times.

The utilization of the total system results from the utilization of all individual sub systems. To achieve a maximum, waiting times at single work steps must not arise. Therefore the work cells must be enabled to run individual cycle times. In theory this could lead to maximal productiveness, if the individual cycle time would be equal to the individual process time of a work station.

The simplest way to gain high efficiency in sub systems is to achieve an average cycle time equal to the average process time of the whole system. To realize this, all single work stations must be able to adjust a specific process time.

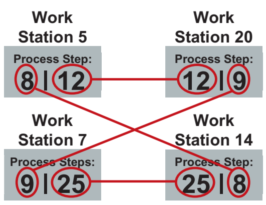

Fig. 4. Dynamic balancing of work stations

For these adjustments it is helpful that only average process times resulting from several processes have to be dealt with. This offers the potential to execute different processes of different durations in variable quantities. In case of assigning at least two differing work contents with different process times to one work station and deciding which process will be executed in what frequency, nearly any conceivable average cycle time can be chosen as long as it does not exceed the longest process or falls below the shortest.

It should be mentioned that in theory a virtual infinite number of throughputs could be needed in order to find the exact average cycle time. In practical application this aspect can be neglected.

Problems arising from the fact that every single work step has to be executed in the same amount – otherwise production stocks would build up – can be solved if the idea of switching work steps is expanded. As well as work steps within a work station system can be time-balanced also several work stations can be balanced within a pool of them. Fig. 4 indicates how two work steps can mutually balance, even if none of the work stations is equipped for both of the balanced work steps.

Finally the complete production system accumulates to a unity of several work stations which can achieve a maximal utilization by dynamic adjustments. In summery the concept of the so called Matrix-Production represents a highly dynamic system that can control and balance temporary fluctuations (for details see section 3.2). Sub systems (work stations for example) within the Matrix-Production act autonomous and can be operated at variable cycle times without creating inflictions or interruptions to other sub systems. Defining each work station as sub system, the fusion of all work stations to a comprehensive system is guaranteeing high utilization because of its dynamic reconfigurability and process flexibility. Diverse process times are compensated within the systems and especially by the control system. Referring to changing market demands and competitors, the Matrix-Production allows an extreme market flexible mixed production keeping utilization at least similar to that of classical assembling lines if not superior to it. As a basic principle technical conditions have to be altered to enable every work station to cope with at least two work steps. The applied conveying systems must answer this demand.

3.1. Hypothetical example

The following example demonstrates in a simplified way the function of the Matrix-Production as described above. It is assumed that three process steps with different process times are required (see table 1). Nine equal work stations are provided as illustrated in Fig. 5a.

Table 1. Process times per process steps.

Process Step No.	Process time [min.]
1	2.4
2	2.7
3	3

As indicated three parallel production lines are obvious. The challenge of the illustrated adjustment of process steps

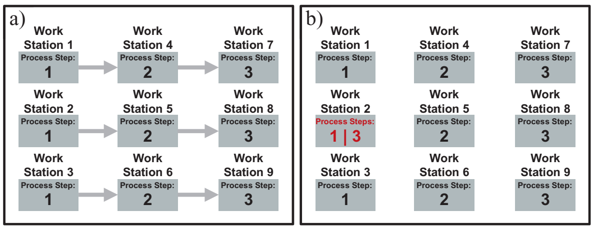

Fig. 5. (a) Initial adjustment; (b) Possible readjustments

and work stations are the different process times. The longest process step (no. 3) determines the current cycle time of 3min. for all workstations. Hence waiting times occur at the workstations with process step 1 or 2. The maximum utilization would be realized, if the average cycle time is equal to the average process time of 2.7min.

Applying the concept of the Matrix-Production on this very easy and static issue Fig. 5b indicates one possible solution. Work station 2 is now adjusted to be able to deal with two different work steps (1 and 3). In this example work station 2 uses 1/3 of its work capacity to execute process step 3 and 2/3 of its work capacity for process step 1. Thus the average cycle time of the work stations 1, 2, 3, 7, 8 and 9 now is 2.7 min. and equal to the average process time of the whole system. The remaining Workstations are already operating with a process time of 2.7min.

Table 2 demonstrates the production of 120 products assigned to the given work stations. 108 min. are necessary to produce 120 units at each process step. This means the average cycle time of 2.7 min. is realized. Compared to the cycle time of 3min. (see Fig. 5a) the utilization has now increased by 10%.

However this is a very static example. The ability to deal with high variation is based on a more complex adjustment of the production system and on a dynamic control system.

Table 2. Quantity of Products (Pr) handled per work station and process step in 108 minutes.

Work station No.	Process step No.		
	1	2	3
1	$\frac{108\,[min]}{2.4\left[\frac{min}{Pr}\right]} = 45$		
2	$\frac{108\,[min]}{2.4\left[\frac{min}{Pr}\right]} = 45$		
3	$\frac{108\,[min]}{2.4\left[\frac{min}{Pr}\right]} \times \frac{2}{3} = 30$		$\frac{108\,[min]}{3.0\left[\frac{min}{Pr}\right]} \times \frac{1}{3} = 12$
4			$\frac{108\,[min]}{3.0\left[\frac{min}{Pr}\right]} = 36$
5			$\frac{108\,[min]}{3.0\left[\frac{min}{Pr}\right]} = 36$
6			$\frac{108\,[min]}{3.0\left[\frac{min}{Pr}\right]} = 36$
7		$\frac{108\,[min]}{2.7\left[\frac{min}{Pr}\right]} = 40$	
8		$\frac{108\,[min]}{2.7\left[\frac{min}{Pr}\right]} = 40$	
9		$\frac{108\,[min]}{2.7\left[\frac{min}{Pr}\right]} = 40$	
$\sum$	120	120	120

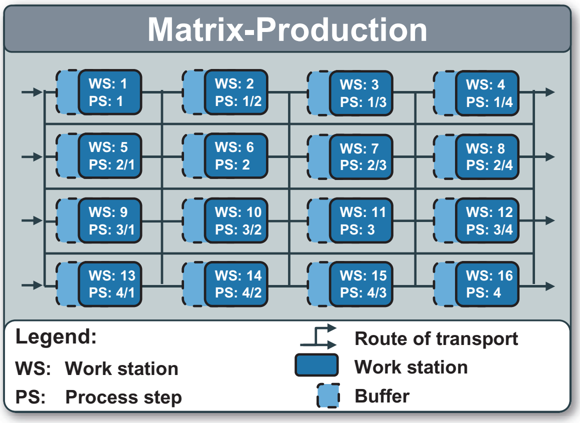

Fig. 6. Schematic design of the Matrix-Production

3.2. Design

The layout of the Matrix-Production differs evidently from that of the traditional assembly line. A continuous direction in transport is abandoned and substituted by variable transport routes between working stations. These stations should be arranged parallel to each other. To optimize the stations` alignment the frequency of occurrence in using possible ways has to be taken into account. Often a rectangular matrix shaped alignment is resulting from the routes. The term Matrix-Production derived from this fact. The ability of balancing mismatched cycle times as well as the robustness against dysfunctions is significantly influenced by the allocation of process steps to work stations and by the afforded buffer capacity. An allocation that allows balancing every single process step to another would be favorable. Fig. 6 shows the basic layout of Matrix Production. Each single station is equipped for operating two different process steps. The resulting redundancy can be executed in horizontal and vertical ways. So a matrix structure is formed. In this basic model all possible combinations of process steps are available twice.

3.3. Evaluation of the matrix structure approach

Evaluation of the Matrix-Production will mainly be realized in a manner specific to the application. Additional raising costs - mainly driven by logistics and necessity of extended space - will be compared to increased efficiency in a classical way. Beyond this it will be investigated how to value the achieved flexibility. Yet another aspect in evaluating is the expected benefits in quality due to the robustness against interruptions. The system continually guarantees sufficient cycle time, so rates of failure will decrease significantly. Because of the complexity and dynamic of this new approach it is necessary to evaluate technical and economic feasibility by simulation.

4. Outlook

Following researches will be related to the optimization and evaluation of the matrix structure approach. Key aspects are algorithms for the system layout and the allocation of process steps to work stations as well as the development and evaluation of different control strategies. Decentralized control “push”-algorithms are expected to work well with the matrix structures. Especially in the context of the Industry 4.0 research area and new decentralized control solutions, these matrix structured production systems can be a promising case for application

The system performance is furthermore significantly influenced by its design. Miscellaneous configurations have to be examined in this field. Especially the redundancy in arranging work stations and the distribution of process steps will decidedly influence the complete system's quality. Transport distances have to be optimized according to their dimensions and frequency of use. Furthermore the Matrix-Production deeply affects process and product designs. Guidelines for innovative designs can be derived. For example it is beneficial to use equal components and tools for different process steps. This offers simple options to equip work stations for differing tasks. At the same time it might not be longer compelling to keep a constant sequence in assembling components from a product-technical point of view. Technical and logistic requirements will be analyzed as well. In addition to the technology of transporting the products, the supply of material and items will be of special interest. The materials and parts must be classified to categories in order to design a fluent supply chain concept. Reflections partly lie upon using the same transport systems for supplies and manufactured products, a separate one or forming a combination of the two. It is worth considering to apply containers to the transport device which carry the supplying items and can be refilled at special logistic stations. Furthermore, classical concepts like just-in-sequence-delivery and the complete factory structure have to be analyzed as well

A further important issue is the improvement of working conditions for employees which has to be stated and valued as well. The Matrix-Production gives scope for individual considerations according to worker’s needs. Benefits are expected in the following sectors:

- Disabled workers with reduced performance can be integrated into the producing process
- Reduction of stress due to the system's ability to react flexible upon less output at single work cells
- Machines adapt to humans which will subjectively cause feelings of far more independence and subsequently to job satisfaction. A good feeling of self-determination is provided by less compulsion to perform totally hooked on a machine
- In satisfactory jobs people only at rare intervals are incapable to work. Motivation is increased
- An individual arrangement of working environment within a certain range is possible and will add to job satisfaction

The modular composition of Matrix-Production structures and the dynamic accessibility of stations will be further objects of research. The combination of stations with differing output factor will be part of this. Also in focus is the integration of fully automatic stations or sections of existing assembly lines. To incorporate special stations like quality inspection or refinishing operation is another challenge.

The concept of the Matrix-Production still must be correlated to existing production theories. Another theoretical approach to the pursued mode of operation is a differentiation between the physical layout and the operation-layout. Parallel to the physical design a virtual layout can be deduced which represent the current configuration. It proves that the excellence of the Matrix-Production is due to its ability to be reconfigured into nearly unlimited amounts of different operation-layouts. The key feature of the Matrix-Production, the dynamic modification of work contents, can also be transferred onto larger systems. In this context research will be done how to apply the concept to complete plants, including component supplier plants.

5. Conclusion

In the automotive industry the product variety and the complexity of products and components are still increasing. The introduction of electromobility, the growing importance of mechatronics, the demand for mass customization, and the diversification of global markets contribute to this trend. As a result, high numbers of different specialized variants of products and components have to be manufactured and assembled. Thus it is of great importance to achieve flexible and scalable production systems for high volume production. However, traditional assembly line concepts struggle to maintain a high utilization while producing components with a high variance in processing times on the same line.

Constant cycle times are required but cannot be achieved if similar component variants need different processing times for the same assembly steps. This causes an unbalanced flow through assembly due to blocking or starving of work stations. Hence, a classical assembly line is unsuitably to perform at a high economic efficient level with respect to future production requirements. Alternative and innovative system configurations are urgently required. Main objective of this new approach is a manufacturing concept that realizes flexibility and scalability that provide high product volume and divergence. The idea of the so called Matrix-Production is based on the set-up of a high process flexible assembly system. It guarantees the requested product, production and volume flexibility. Main principle for achieving the aim is the elimination of equal cycle times while sustaining a fluently running process. This is made possible by providing every work cell with multiple work steps. By altering and prioritizing these work steps, different process times resulting e.g. from different product variants can be balanced. An appropriate flexible transport system affords a dynamic distribution of material to the work cells. Of special relevance is the control system that ensures a high utilization. If suitable adjusted, the control system can also deal with disruptions and thus keep the production system extremely robust. The need for a simulation approach is required for the evaluation of the matrix structure approach due to many dynamic factors and dependencies in the assembly system. This simulation model will be developed based on the requirements of the automotive industry using different types of production control algorithms.

Finally the new approach leads to the conclusion that discrepancies between flexibility and efficiency are not only resolved but the demand for maximum capacity will necessitate the application of more flexible systems.

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